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Pressurized testing of a planar solid oxide fuel cell stack

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ABSTRACT

Gas leakage often occurs in planar solid oxide fuel cell (SOFC) stacks due to small pressure differentials (2–3 psi) between the process flows and external pressure. This gas leakage can initiate localized burning and degradation mechanisms, which result in lower stack efficiency, reduced stack lifetime, and higher overall cost. A more durable planar SOFC design that can accommodate higher operating pressure would contribute to higher efficiency and more versatile SOFC system integrations. This manuscript examines the performance of a 60-cell, planar SOFC stack up to 45 psia. SOFC stacks can be successfully operated at elevated pressure by containment in a pressure vessel and equalization of the vessel pressure to the process pressure (i.e. anode and cathode gas flows). SOFC stacks display pressure-dependent voltage in accordance with theory, suggesting that an absolute efficiency gain of 2–3% by operating at 45 psia versus ambient pressure (15 psia) is achievable.

1. Introduction

The Naval Undersea Warfare Center, Division Newport (NUWCDIVNPT) has been working to implement solid oxide fuel cell (SOFC) technology into Unmanned Undersea Vehicle (UUV) applications [1–3]. Recent work has involved testing state-of-the-art SOFC stacks, fuel processors and balance of plant components to obtain performance metrics for 1–5 kW integrated systems. System-level demonstrations carried out at pressures slightly above ambient (2–3 psig) have successfully validated anode recycle and pure oxygen operation, but higher pressure operation is necessary for SOFC-powered UUVs to perform reliably and sustainably at peak efficiency.

SOFC systems can offer higher energy storage metrics than existing rechargeable batteries or other energy system options for undersea platforms. The ability to operate at elevated pressure would enhance system efficiency as well as facilitate overboard venting of exhaust gases if required. Furthermore, the higher system-level efficiency positively impacts total energy storage, UUV endurance (capability), and overall ownership cost. Pressure-induced gains in system efficiency have already been realized for land-based systems such as high-pressure reformate streams produced from gasification processes and fuel cell integration with gas turbines [4,5].

SOFC stacks are generally operated with strict pressure regulation near ambient pressure. A typical planar stack is not rated for pressures higher than 2 psig, and this reflects the delicate nature of the stack seals. The methods for sealing planar SOFC cells have varied over the years, with a majority of materials based upon either compressive, mica-based seals, rigid glass-ceramics, or brazed seals [6]. In an attempt to impart hermeticity, some compressive-based seals have

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employed a thin, viscous glass layer for bonding between the metallic interconnect and ceramic gasket, and this is the type of seal used in the stack evaluated in this study.

To date, there have only been a few validations of pressurized operation [7–14], especially for planar SOFC stacks. The primary deterrent to pressurized operation in planar SOFCs is cell-to-cell sealing, which can fail when excessive pressure differential exists between anode and cathode or process gas and atmosphere [15]. Because the rate of gas leakage is directly proportional to the pressure differential, equalizing the external stack pressure to the process (anode and cathode) pressure minimizes the primary driving force for gas leakage and in doing so increases the durability of planar stacks for pressurized operation. Therefore, this study focused on validating a suitable technique for pressurized SOFC stack operation and evaluation by enclosing the stack within a pressure vessel and balancing pressures across the three different zones (cathode, anode, and vessel). The approach to making a stack more tolerant of elevated pressure is the effective removal of the underlying pressure differentials at the stack that can lead to cell/seal fracture, gas leakage, and ultimate failure. Appropriate construction of the stack containment vessel, process control to monitor stack pressures, and gas analysis are all used to increase the performance and reliability of SOFC stacks at elevated pressure. In contrast to earlier studies, it should also be noted that this SOFC stack was only heated to 700 °C instead of 750–800 °C and that the cathode was lanthanum strontium cobalt ferrite (LSCF) instead of lanthanum strontium manganite (LSM).

2. Experimental method

2.1. SOFC stack

A nominal 1.5 kW stack was supplied by Materials and Systems Research, Inc. (MSRI), and the test was conducted by NUWCDIVNPT. Fig. 1 shows the set-up for testing MSRI's SOFC stack within a pressure vessel. The MSRI SOFC stack consists of 60 cells that are metal-brazed onto SS430 interconnects. Glass-mica sealing gaskets are placed between each cell for electrical and gas-flow isolation, and external, spring-loaded compression is applied to the stack for sealing and ensuring electrode contact between individual cells. The cells are anode-supported, thin film YSZ-electrolyte planar cells with active area of 10 cm × 10 cm. The anode is a 67/33 Ni/YSZ cermet with a nickel mesh contact aid, and the cathode is LSCF with a silver mesh contact aid. Functional interlayers were applied on both electrodes, and a cross-sectional image of the cell can be seen in Fig. 2. Thirty-one cell leads were provided from the 60-cell stack to monitor the voltage between every set of two consecutive cells in the stack (termed here as double cell voltage). The stack is of cross-flow design and is intended for operation between 700 and 850 °C. The lower end of operating temperature (700 °C) was selected because adequate thermal management of the stack is a concern in UUV operations. Excess air is not available for cooling; therefore, lower current density and operating temperatures are targeted versus land-based, air-breathing systems.

2.2. Pressure Test Vessel

Fig. 1 depicts images of a 50-inch ID carbon steel Pressure Test Vessel at various stages of assembly. The SOFC stack was enclosed in the vessel, and gas connections and scaffolding were made of stainless steel. Zircar Microsil insulation was used to form an insulating box around both the stack and Thermcraft Fibercraft heating elements. Additional kaowool insulation covered the inlet lines, exhaust lines and hot zone volume. Watlow Firerod heaters were employed to pre-heat the SOFC gas feeds, and Model 3504 Eurotherm controllers regulated the SOFC furnace and in-line gas heaters. Conax fittings provided pressure-tight seals around all wires and thermocouples that passed through the pressure vessel wall. Equilibar back-pressure regulators balanced the pressure in the three zones (vessel, anode, and cathode), and a QPV controller was used to control a single reference pressure for the three Equilibar regulators. Labview Realtime data acquisition and controls were configured for remote operation of the test.

2.3. Pressure control

Pressurized testing of the SOFC stack was conducted up to 45 psia (3 atm). The vessel was purged and pressurized with argon gas during testing in order to detect gas leakage from the stack and equalize the pressure external to the stack with the internal anode and cathode stack pressures. A control algorithm was encoded in Labview to prevent pressure rate change larger than 0.5 psi/min unless an abort alarm triggered, in which case the system vented to ambient pressure immediately. In most cases, changing the vessel pressure was conducted at constant gas flow in order to facilitate pressure balancing in the three zones and monitoring of performance as a function of pressure. For this demonstration, all exhaust back-pressure regulators were referenced to the same back-pressure reference gas. Control accuracy to within 0.1 psi was demonstrated.

2.4. Operating conditions

Preliminary testing of the SOFC stack utilized dry 50% H_2/50% N_2 (by volume) mixtures at the anode and air at the cathode to establish baseline ambient pressure performance metrics. After these baseline tests at 700 °C were conducted, the pressure vessel was closed and pressurized testing commenced. The maximum rated operating temperature of the pressure vessel at 165 psia is 204 °C. While the stack furnace exceeded this temperature, it was sufficiently insulated and radiated heat over a large enough area to prevent localized heating of the vessel. The highest internal vessel wall temperature measured during operation was approximately 95 °C at 45 psia, as verified by infrared thermography. A maximum heating rate of 4 degrees/min was attained with the SOFC stack furnace.

2.5. Mass spectrometry measurements

Gas leakage and/or crossover in the stack were monitored from dry gas measurements using an 8-channel Mound Technical Mass Spectrometer (MS) controlled by a remote desktop